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SR07 Small Racetrack Magnet Test Summary

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1. Introduction

Small racetrack (SR) coil magnet SR07 was built at Fermilab using 28-strand rectangular Rutherford cable made of 1-mm diameter Ta-matrixed Nb_3Al (F4) strand. The F4 Nb_3Al strand was manufactured at National Institute for Material Sciences (NIMS) in Japan. The characteristics of the F4 strand with its short sample data are shown in Appendix I, In more details these characteristics will be reported at the Applied Superconductivity Conference in Chicago (ASC 2008) [1]. Previously the SR04 magnet with the Nb-matrixed Nb_3Al (F1) cable was built and tested at Fermilab [2], [3], but this magnet exhibited low field instabilities due to Nb matrix and not enough twisting in the F1 strand.

The SR07 magnet was delivered to the Fermilab magnet test facility in the beginning of July and it was electrically checked by July 8th 2008. The VMTF dewar was filled with liquid helium on July 10th and the magnet test was started on July 11th. The test was completed on July 18th. Warm up was started on the same day and the room temperature was reached early morning of July 23rd.

The SR07 magnet was excited up to 25.2 kA at 2.2 K without any instability. The test results will be reported at the ASC 2008 [4].

The Voltage Spike Detection System (VSDS) was used for detection of small magnetic flux changes in the magnet. Results of the SR07 spike data analyses, as well as of the magnet mechanical analyses, will be presented in a separate note.

2. Instrumentation

The total length of cable in the SR07 magnet is ~14 m. Two racetrack coils are wound in opposite direction with the 2-mm gap between them. There are 13 turns of cable per layer. Cable parameters are listed in Appendix II.

Voltage tap system covers both coil layers. There are voltage taps before and after the splice at each lead, a voltage tap between the layers and 2 voltage taps on each layer. Schematic view of the magnet with the voltage tap locations is shown in Fig.1. Further in the text or plots “top” coil stands for the racetrack magnet layer at the negative power lead and “bottom” coil – for the layer at the positive power lead.

9 strain gauges were installed on the aluminum skin for monitoring mechanical strain during the magnet construction and testing.

In addition to the standard set of the dewar sensors two additional resistive temperature devices (RTD) *Cernox cx43235* and *cx43233* sensors were mounted on top and bottom of the magnet body respectively.

Magnet was connected to the 30 kA top plate. Due to extremely small inductance ~ 22 μH, the current ripple of the power supply should be kept at minimum using the well adjusted regulator. Current noise was within ±25 A at the magnet current of ~25 kA.

One spot heater was installed on outer turn of bottom layer at the lead end. Heater firing unit (HFU) bank capacitance and voltage was set to 2.4 mF and 30 V respectively. No protection heaters were installed on the magnet.

The quench detection threshold for the half-coil signal was set to 1.0 V (signals from the bottom layer formed the 1st half-coil signal, and signals from the top layer - the 2nd half-coil signal).

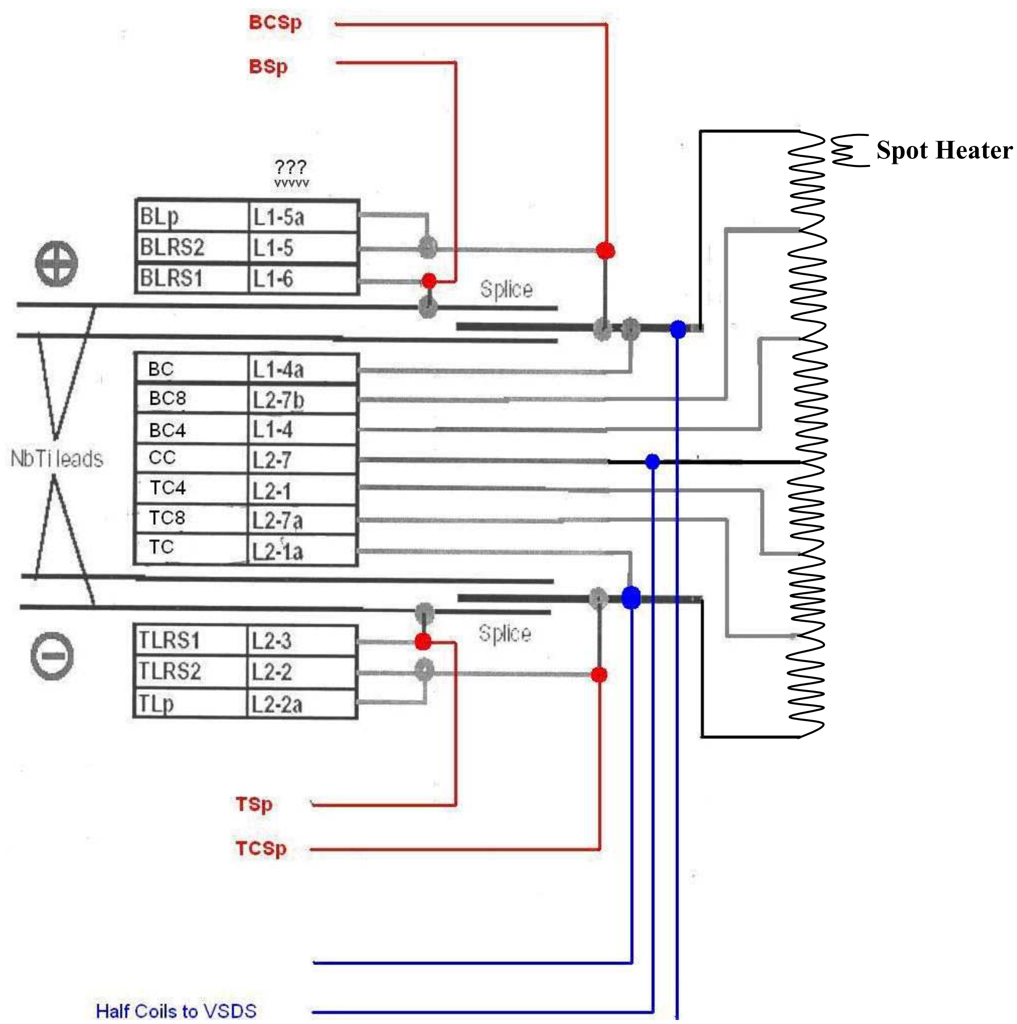

Figure 1. SR07 schematic view.

3. Quench History

The magnet cold test program started at 4.5 K with quench training at the 20 A/s ramp rate. In the beginning we had a trip in the superconducting (SC) lead section, specifically between the welded joint at the positive copper power lead underneath the top plate and the NbTi splice segment. No signal was observed in the splice segment, so we increased the liquid helium level up to ~ 27-28 cm (with the maximum level of 32 cm). Apparently the mechanical and electrical joint at the positive lead was generating heat and in the following 6 quenches we also had the positive lead trips.

Next we started increasing the ramp rate and finally, with the 150 A/s ramp rate, the quench at 21.4 kA developed in the top coil. Following ramp at 200 A/s also confirmed that fast ramp up was necessary to avoid the lead trips due to the accumulated heat.

Full quench history of the SR07 magnet test is presented in Fig.2. Quenches at high ramp rates, 200 A/s and more, usually develop in both layers, but we always quote one of the layers, where the resistive signal starts earlier and is stronger than the signal from the another layer, as an origin of the quench development.

The ramp rate increase from 20 A/s to 125 A/s in the beginning of test (see Fig.2) is increasing the current at which the SC lead is tripping. At the 100 A/s ramp rate we had both the lead trip (quench #7 at 2.13 kA) and the real quench in the magnet (quench #16 at 2.4 kA). It indicates that, in average, 215-220 sec were necessary at 4.5 K to accumulate heat enough for a lead trip. This time was sensitive to the liquid helium level in the vessel, which was fluctuating ± 5-10 % around the setting value.

Test was continued with the ramp rate study, results are presented in Section 4. Test at 4.5 K was finished with the energy loss measurements.

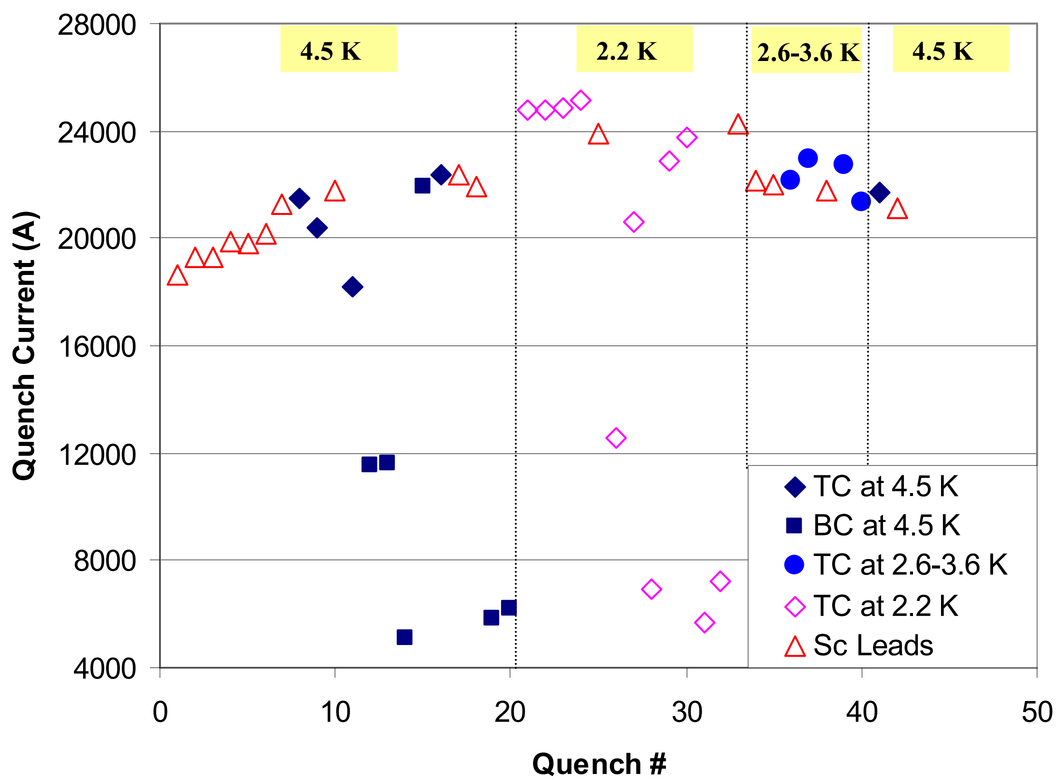

Figure 2. SR07 quench history.

Test at 2.2 K was limited with the ramp rate study. Since we had limited time left for the test, it was decided to skip training at this temperature. The magnet reached almost 25 kA current in the very first quenches, but still we had lead trips at the ramp rate of 20 A/s.

After the quench #33 we started warming up the magnet, taking data for study of the quench current dependence on the temperature.

At the end of the cold test we confirmed the real quench with the 150 A/s ramp rate and the lead trip with the 20 A/s ramp rate at 4.5 K.

The highest quench current achieved was 22450 A at 4.5 K (the quench # 16 at 100 A/s ramp rate) and 25190 A at 2.2 K (the quench # 24 at 50 A/s ramp rate). The complete quench history is presented in Tables 1 and 2.

All quenches in both the top and bottom layers developed in the inner segment (***CC-TC4*** and ***BC4-CC*** in Fig.1). The bottom layer mostly was quenching at very high ramp rates (500 A/s and up). Quench multiplicity in coils at different temperatures are shown in Fig.3.

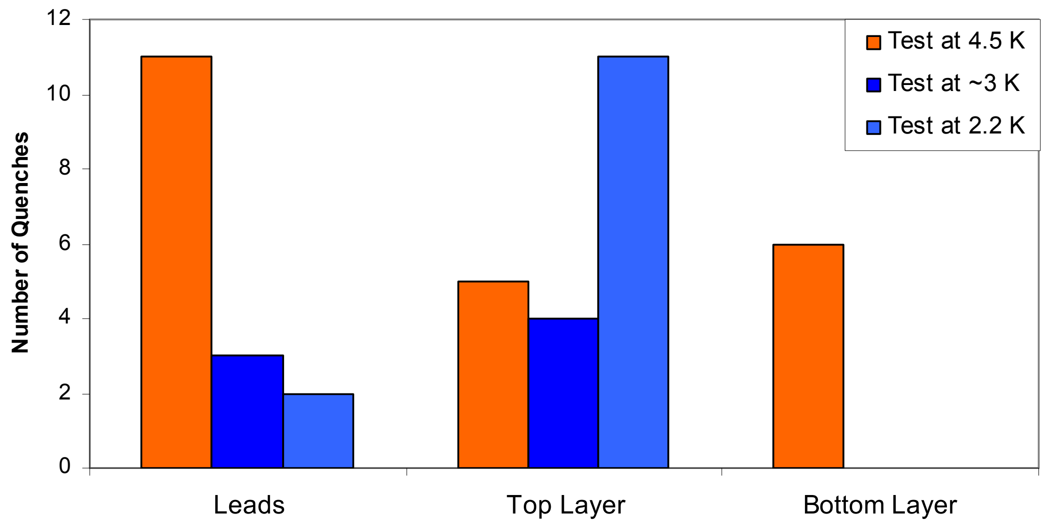

Figure 3. Quench multiplicity in coils

Spot heater test was not performed due to lack of time.

Thermal tests were conducted on July 14th in order to estimate copper block joint resistance on the 30 kA top plate. Goal of this study was to understand if the copper to NbTi lead joint caused several lead trips during the SR07 cold test.

The system heat load data was collected by reading the lead flow rotameters at a different current on magnet (0 – 15 kA). Each current level was held for 15 minutes with the steady liquid helium level and no bypasses open.

The joint resistances were calculated in two ways. The first was to plot heat load dependence on the magnet current and do the parabolic fit to data using the function $Q = Q_{STATIC} + I^2 * R$. The second calculation used the heat load difference between the data points (at 10 kA and 15 kA), i.e. canceling the static heat load out of the calculations. Both calculations gave similar results on the total resistance of the copper block ~ 510-540 nOhm. For comparison, the copper block resistances for the 15 kA top plate were 15.5-18.0 nOhm. More than an order of magnitude difference in resistances may indicate pure quality of the above mentioned joint on the 30 kA top plate.

Table 1: SR07 Quench History with comments

File	#	I (A)	dI/dt (A/sec)	t_{quench}	MIITs	QDC	Top-Bot ave. T (K)	Comments [notes in brackets were added later]
sr07.Quench.080711145218.003		1000	20	0.0000	0.07	DQDcoil	*4.52*	We did AQD & DQD balancing before this manual trip at 1000 A
sr07.Quench.080711155641.849	1	18638	20	-0.1784	0.00	SlWcoil	*4.55*	AQD leads trip at 18600A, 4.5K
sr07.Quench.080711164234.355	2	19325	20	-0.1633	0.00	SlWcoil	*4.55*	AQD lead trip at 19279A, 4.5K
sr07.Quench.080711174133.398	3	19273	20	-0.1631	0.00	SlWcoil	*4.55*	quench at 19.3kA, DQD leads tripped, 4.5K
sr07.Quench.080711181837.862	4	19921	30	-0.1389	0.00	SlWcoil	*4.55*	DQD leads tripped at 19879A, 4.5K
sr07.Quench.080711184717.894	5	19813	50	-0.1481	0.00	SlWcoil	*4.54*	quench at 19.8kA, ramp rate 50A/s, 4.5K
sr07.Quench.080711190255.566	6	20205	50	-0.1358	0.00	SlWcoil	*4.54*	Quench at 20.2kA with ramp rate 100A/s upto 18kA and then at 50A/s. 4.5K
sr07.Quench.080712110119.546	7	21269	100	-0.1199	0.00	SlWcoil	*4.46*	quench at 2128A, ramp rate 100 A/s, AQD leads tripped.
sr07.Quench.080712113820.105	8	21456	150	-0.0167	6.27	WcoilGnd	*4.45*	quench at 21377A with ramp rate 150A/s, 4.5K
sr07.Quench.080712121233.062	9	20390	200	-0.0043	2.55	SlWcoil	*4.45*	quench at 20293 A/s, ramp rate 200 A/s 4.5K
sr07.Quench.080712124811.388	10	21805	125	-0.1057	0.00	SlWcoil	*4.45*	quench at 21756A with ramp rate 125 A/s, 4.5K
sr07.Quench.080712130519.931	11	18215	300	-0.0084	3.41	WcoilIdot	*4.44*	quench at 17939 A with ramp rate 300 A/s, 4.5K
sr07.Quench.080712132358.842	12	11595	480	-0.0302	4.37	SlWcoil	*4.44*	quench at 11392A with ramp rate 600 A/s, 4.5K
sr07.Quench.080712135140.575	13	11590	480	-0.0293	4.23	WcoilIdot	*4.44*	quench at 11.4kA with ramp rate 800 A/s (due to low acceleration the real ramp rate is less) 4.5K
sr07.Quench.080712140540.237	14	4877	800	-0.4754	0.40	WcoilIdot	*4.44*	quench at 5000 A with ramp rate 800 A/s (accel. was 150 A/s^2), 4.5K
sr07.Quench.080714173611.415	15	21997	150	-0.0025	2.14	SlWcoil	*4.46*	Ramp to quench after holding 5kA for ~1hr. Quench at 21944A with the ramp rate of 150 A/s, 4.5K
sr07.Quench.080714181535.138	16	22452	100	-0.0025	2.17	WcoilIdot	*4.47*	quench at 22400A with ramp rate 100A/s. 4.5K
sr07.Quench.080714191620.650	17	22393	50	-0.0902	0.00	SlWcoil	*4.47*	quench at 22340A with ramp rate 50A/s, 4.5K
sr07.Quench.080714194127.605	18	21981	50	-0.1085	0.00	SlWcoil	*4.47*	ramp to 20kA@150A/s and then to quench @ 50A/s. Quench current 21956A, 4.5K
sr07.Quench.080715162412.119	19	5868	765	-0.2076	7.23	GndRef	*4.45*	quench at 5600A with ramp rate 800A/s. Energy loss meas. at 4.5K

sr07.Quench.080715163303.186		5	0	-0.3685	6.40	HcoilHcoil	*4.45*	trip at 0A, energy loss measurements
sr07.Quench.080715174347.352	20	6242	545	-0.1542	6.04	GndRef	*4.45*	quench at 6.2kA with ramp rate of 700A/s, 4.5K
sr07.Quench.080716143251.515	21	24852	100	-0.0014	1.92	SlWcoil	*2.15*	First quench at 2.1K with ramp rate 100A/s, I=24796A.
sr07.Quench.080716154939.114	22	24830	100	-0.0018	2.13	WcoilIdot	*2.15*	quench at 24805A with ramp rate 100A/s, 2.15K
sr07.Quench.080716161801.604	23	24749	100	-0.0007	1.50	WcoilIdot	*2.15*	quench at 24826A, 100A/s, 2.15K
sr07.Quench.080716165158.510	24	25191	50	-0.0017	2.11	SlWcoil	*2.15*	quench at 25167A with ramp rate 50A/s, 2.15K.
sr07.Quench.080716172342.388	25	23952	20	-0.0816	0.00	SlWcoil	*2.15*	quench at 23910A, ramp rate 20A/s (50A/s upto 20kA), 2.15K
sr07.Quench.080716173628.887	26	12531	500	-0.1218	1.99	WcoilGnd	*2.15*	quench at 11450A with ramp rate 500A/s, 2.15K
sr07.Quench.080716175447.982	27	20630	300	-0.0049	2.85	SlWcoil	*2.15*	quench at 20500A, ramp rate 300A/s, 2.15K
sr07.Quench.080717095103.122	28	6778	600	-0.3202	0.79	HcoilHcoil	*2.15*	quench at 6700A, 600A/s, 2.15K
sr07.Quench.080717102450.253	29	22844	200	-0.0038	2.93	SlWcoil	*2.15*	quench at 22742A, 200A/s, 2.15K
sr07.Quench.080717105558.191	30	23826	150	-0.0146	7.60	SlWcoil	*2.15*	quench at 23790A, 150 A/s, 2.15K
sr07.Quench.080717111435.601	31	5710	800	-0.2471	0.52	GndRef	*2.15*	quench at 5502A, 800A/s, 2.15K
sr07.Quench.080717113244.233	32	7101	600	-0.2921	0.79	WcoilIdot	*2.15*	quench at 7kA, ramp rate 600A/s, 2.15K
sr07.Quench.080717120326.516	33	24298	20	-0.0805	0.00	SlWcoil	*2.15*	quench at ~24.2KA with ramp rate of 20 A/s (150A/s upto 20kA), 2.15K
sr07.Quench.080717124025.098	34	22203	150	-0.1252	0.00	SlWcoil	*2.59*	quench at 22kA 150A/s 2.15K
sr07.Quench.080717125053.190	35	22032	150	-0.1315	0.00	SlWcoil	*2.60*	quench at 21999A, 150A/s, 2.15K
sr07.Quench.080717141951.967	36	22243	200	-0.0035	2.61	SlWcoil	*3.00*	quench at 22148A, 200A/s, 3K
sr07.Quench.080717144852.778	37	22975	150	-0.1040	0.00	SlWcoil	*3.01*	quench at 22922A, 150A/s, 3.01K
sr07.Quench.080717160519.229	38	21811	150	-0.1266	0.00	SlWcoil	*3.62*	quench at 21788A, 150A/s, 3.6K
sr07.Quench.080717162400.905	39	22748	150	-0.0028	2.33	SlWcoil	*3.63*	quench at 22691A, 150A/s, 3.62K
sr07.Quench.080717165047.875	40	21420	200	-0.0032	2.33	SlWcoil	*3.65*	quench at 21355.1A, 200A/s, 3.62K
sr07.Quench.080718115323.344	41	21715	150	-0.0034	2.49	SlWcoil	*4.48*	quench at 21669A, 150A/s, 4.5K
sr07.Quench.080718122043.085	42	21169	20	-0.1133	0.00	SlWcoil	*4.51*	quench in leads at 2.1kA, 20 A/s (150A/s to 20kA)

Table 2: SR07 Quench History with parameters for the first two quenching segments

File	#	I (A)	dI/dt (A/sec)	t_{quench}	MIITs	QDC	1st VTseg	t_{rise}	2nd VTseg	t_{rise}	Top-Bot T ave. (K)
sr07.Quench.080711145218.003		1000	20	0.000	0.07	DQDcoil	-	0.000	-	0.000	*4.523*
sr07.Quench.080711155641.849	1	18638	20	-0.178	0.00	SlWcoil	SlbsPos	-0.178	SlPos	-0.178	*4.550*
sr07.Quench.080711164234.355	2	19325	20	-0.163	0.00	SlWcoil	SlbsPos	-0.156	SlPos	-0.163	*4.554*
sr07.Quench.080711174133.398	3	19273	20	-0.163	0.00	SlWcoil	SlbsPos	-0.169	SlPos	-0.169	*4.549*
sr07.Quench.080711181837.862	4	19921	30	-0.139	0.00	SlWcoil	SlbsPos	-0.141	SlPos	-0.141	*4.548*
sr07.Quench.080711184717.894	5	19813	50	-0.148	0.00	SlWcoil	SlbsPos	-0.148	SlPos	-0.148	*4.540*
sr07.Quench.080711190255.566	6	20205	50	-0.136	0.00	SlWcoil	SlbsPos	-0.138	SlPos	-0.137	*4.539*
sr07.Quench.080712110119.546	7	21269	100	-0.120	0.00	SlWcoil	SlbsPos	-0.121	SlPos	-0.120	*4.464*
sr07.Quench.080712113820.105	8	21456	150	-0.017	6.27	WcoilGnd	CC_TC4	-0.004	TC4_TC8	-0.003	*4.448*
sr07.Quench.080712121233.062	9	20390	200	-0.004	2.55	SlWcoil	CC_TC4	-0.005	TC4_TC8	-0.004	*4.452*
sr07.Quench.080712124811.388	10	21805	125	-0.106	0.00	SlWcoil	SlbsPos	-0.105	SlPos	-0.104	*4.449*
sr07.Quench.080712130519.931	11	18215	300	-0.008	3.41	WcoilIdot	CC_TC4	-0.009	TC4_TC8	-0.008	*4.444*
sr07.Quench.080712132358.842	12	11595	480	-0.030	4.37	SlWcoil	BC4_CC	-0.029	BC8_BC4	-0.029	*4.438*
sr07.Quench.080712135140.575	13	11590	480	-0.029	4.23	WcoilIdot	BC4_CC	-0.029	BC8_BC4	-0.029	*4.437*
sr07.Quench.080712140540.237	14	4877	800	-0.475	0.40	WcoilIdot	BC_BC8	-0.245	BC4_CC	-0.245	*4.442*
sr07.Quench.080714173611.415	15	21997	150	-0.003	2.14	SlWcoil	BC4_CC	-0.003	BC8_BC4	-0.003	*4.462*
sr07.Quench.080714181535.138	16	22452	100	-0.003	2.17	WcoilIdot	CC_TC4	-0.003	TC4_TC8	-0.002	*4.469*
sr07.Quench.080714191620.650	17	22393	50	-0.090	0.00	SlWcoil	SlbsPos	-0.090	SlPos	-0.089	*4.472*
sr07.Quench.080714194127.605	18	21981	50	-0.109	0.00	SlWcoil	SlbsPos	-0.108	SlPos	-0.108	*4.469*
sr07.Quench.080715162412.119	19	5868	765	-0.208	7.23	GndRef	BC8_BC4	-0.110	BC_BC8	-0.110	*4.447*
sr07.Quench.080715163303.186		5	0	-0.369	6.40	HcoilHcoil	CC_TC4	-0.162	TC4_TC8	-0.161	*4.447*
sr07.Quench.080715174347.352	20	6242	545	-0.154	6.04	GndRef	BC4_CC	-0.154	BC8_BC4	-0.153	*4.447*
sr07.Quench.080716143251.515	21	24852	100	-0.001	1.92	SlWcoil	CC_TC4	-0.002	TC4_TC8	-0.002	*2.150*
sr07.Quench.080716154939.114	22	24830	100	-0.002	2.13	WcoilIdot	CC_TC4	-0.002	TC4_TC8	-0.002	*2.151*
sr07.Quench.080716161801.604	23	24749	100	-0.001	1.50	WcoilIdot	CC_TC4	-0.002	TC4_TC8	-0.002	*2.149*
sr07.Quench.080716165158.510	24	25191	50	-0.002	2.11	SlWcoil	CC_TC4	-0.003	TC4_TC8	-0.003	*2.149*
sr07.Quench.080716172342.388	25	23952	20	-0.082	0.00	SlWcoil	SlbsPos	-0.082	SlPos	-0.081	*2.149*
sr07.Quench.080716173628.887	26	12531	500	-0.122	1.99	WcoilGnd	CC_TC4	-0.055	TC4_TC8	-0.054	*2.149*
sr07.Quench.080716175447.982	27	20630	300	-0.005	2.85	SlWcoil	CC_TC4	-0.006	TC4_TC8	-0.005	*2.150*
sr07.Quench.080717095103.122	28	6778	600	-0.320	0.79	HcoilHcoil	CC_TC4	-0.142	TC4_TC8	-0.109	*2.153*
sr07.Quench.080717102450.253	29	22844	200	-0.004	2.93	SlWcoil	CC_TC4	-0.004	TC4_TC8	-0.003	*2.151*

sr07.Quench.080717105558.191	30	23826	150	-0.015	7.60	SlWcoil	CC_TC4	-0.003	TC4_TC8	-0.002	*2.147*
sr07.Quench.080717111435.601	31	5710	800	-0.247	0.52	GndRef	BC4_CC	-0.249	BC8_BC4	-0.249	*2.149*
sr07.Quench.080717113244.233	32	7101	600	-0.292	0.79	WcoilIdot	CC_TC4	-0.128	TC4_TC8	-0.096	*2.149*
sr07.Quench.080717120326.516	33	24298	20	-0.081	0.00	SlWcoil	SlbsPos	-0.078	SlPos	0.000	*2.149*
sr07.Quench.080717124025.098	34	22203	150	-0.125	0.00	SlWcoil	SlbsPos	-0.124	SlPos	0.000	*2.589*
sr07.Quench.080717125053.190	35	22032	150	-0.132	0.00	SlWcoil	SlbsPos	-0.130	SlPos	0.000	*2.601*
sr07.Quench.080717141951.967	36	22243	200	-0.004	2.61	SlWcoil	CC_TC4	-0.003	TC4_TC8	-0.003	*2.999*
sr07.Quench.080717144852.778	37	22975	150	-0.104	0.00	SlWcoil	SlbsPos	-0.103	SlPos	-0.102	*3.012*
sr07.Quench.080717160519.229	38	21811	150	-0.127	0.00	SlWcoil	SlbsPos	-0.126	SlPos	-0.125	*3.616*
sr07.Quench.080717162400.905	39	22748	150	-0.003	2.33	SlWcoil	CC_TC4	-0.003	TC4_TC8	-0.003	*3.626*
sr07.Quench.080717165047.875	40	21420	200	-0.003	2.33	SlWcoil	CC_TC4	-0.005	TC4_TC8	-0.004	*3.648*
sr07.Quench.080718115323.344	41	21715	150	-0.003	2.49	SlWcoil	CC_TC4	-0.004	TC4_TC8	-0.004	*4.479*
sr07.Quench.080718122043.085	42	21169	20	-0.113	0.00	SlWcoil	SlbsPos	-0.114	SlPos	-0.113	*4.510*

4. Ramp Rate Dependence

Several quenches were performed for the ramp rate dependence study at 4.5 K and 2.2 K. A plot summarizing all ramp rate quenches is shown in Fig. 4. The ramp rate dependence of the SR04 magnet also is shown in this figure for comparison.

At 4.5 K, in the region of below 100-125 A/s, we see a quench current decrease due to the heating problems at the superconducting leads as described in the previous section. At 2.2 K the similar decrease is observed only at the ramp rate of 20 A/s.

The ramp rate dependence curve at 2.2 K is shifted up for about 250 A relative to the curve at 4.5 K for the ramp rates of 300 A/s and below. The ramp rate dependence curve of the SR04 magnet is roughly 250 A down relative to that of the SR07 magnet for below 200 A/s range, and shows an abrupt decrease at the ramp rate of 300 A/s.

If there were no SC lead trips at low ramp rates and consider only ramp rates in the region of 100-400 A/s we can extrapolate the magnet critical current limit from the ramp rate dependence shown in Fig. 4. The maximum quench currents were estimated as 24.5 kA at 4.5 K and 27 kA at 2.2 K.

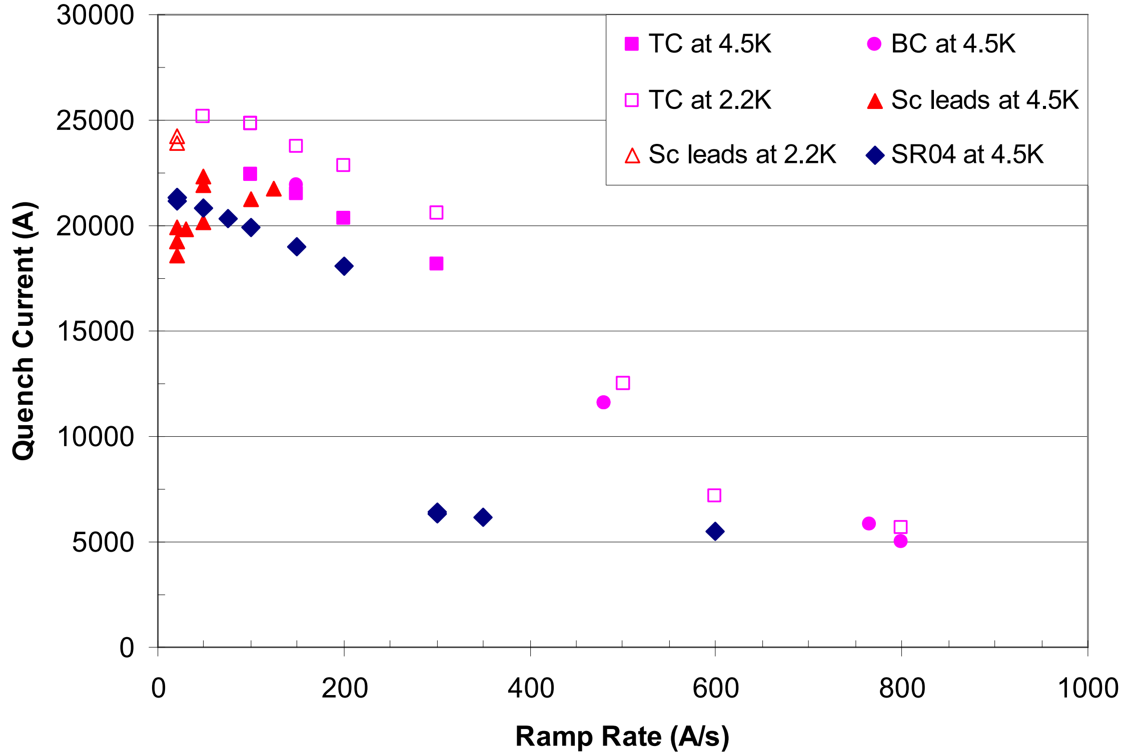

Figure 4. Ramp rate study at 4.5 K and 2.2 K.

5. Temperature Dependence Study

Quench current temperature dependence was studied during the warm-up to 4.5 K after the magnet test was completed at 2.2 K, using two different ramp rates - 150 and 200 A/s. Results are shown in Fig. 5. The nominal ramp rate of 20 A/s was not considered in this study due to the SC lead trips at low ramp rates.

The temperature dependence is smooth for both the ramp rates of 150 A/s and 200 A/s. The SC lead trips at the ramp rate of 150 A/s are also shown in Fig.5.

All quenches at the intermediate temperatures developed in the top layer of the magnet.

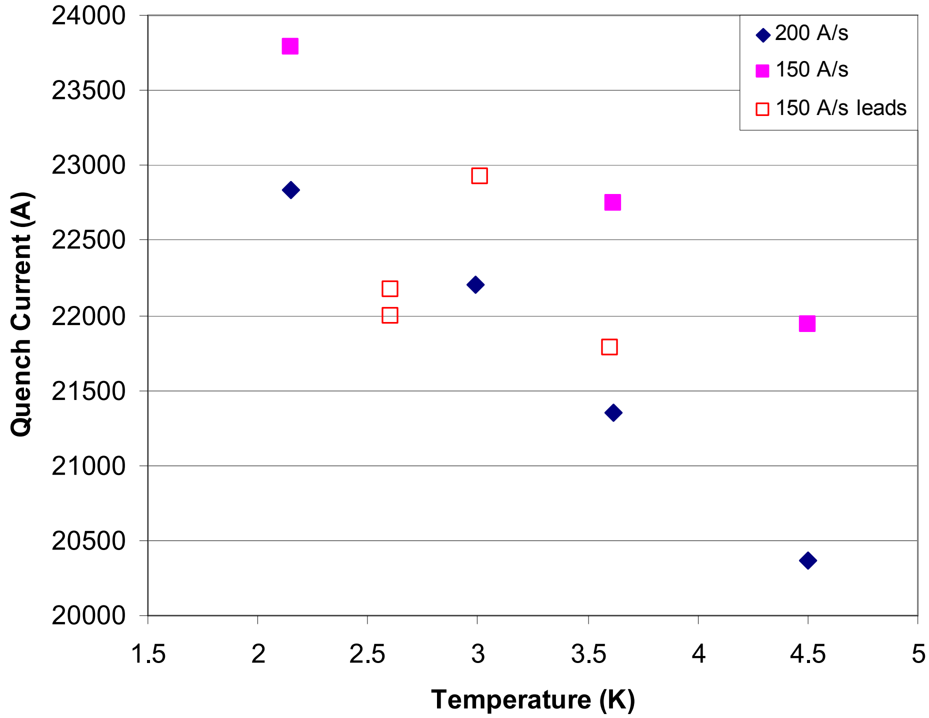

Figure 5. SR07 quench current temperature dependence.

6. Measurement of the Residual Resistivity Ratio (RRR)

Estimates of RRR in SR07 coil segments have been made using data captured during the warm-up after the cold test was completed. The warm-up was started on July 18th and transition from superconducting to normal occurred at early morning of next day and data captured at 01:25 am was used for the cold RRR measurement. Temperature of the magnet was 17.7 K when the transition occurred.

Coil voltages across "configurable" voltage tap segments were monitored by the *Pentek* data loggers, while a current of alternating polarity, +/- 9.7 ± 0.4 A, was put through the magnet. For both warm (~ 300 K) and cold (~ 18 K) measurements we used the RRR amplifier gains for the voltage tap segments to maximize the signal levels.

The magnet reached room temperature on July 22nd and warm voltage measurements were captured on July 23rd at ~11:07 am. Data for all segments are shown in Table 3 and the results are graphed in Fig. 6.

7. Energy Loss Measurements

Energy loss measurements were made as a function of ramp rate to study AC losses from eddy currents and iron/conductor magnetization. Measurements were done using the existing system utilizing VME modules in the *VxWorks* real-time operating system to communicate with a 3458 DVM. Therefore, in the text or figures we refer to this measurement system as a *VxWorks* system.

The energy loss measurements were performed on July 15th at 4.5 K temperature. Sawtooth ramps from 500 A to 6500 A were used to measure energy losses as a function of ramp rate in the range 200-600 A/s. 5 measurements were taken for each ramp rate. Results and the linear fit to the data are shown in Fig.7 The fit intercept, corresponding to the hysteresis energy loss, is ~ 65 J. The fit slope, measuring losses from eddy currents, is 0.16 J/A/s.

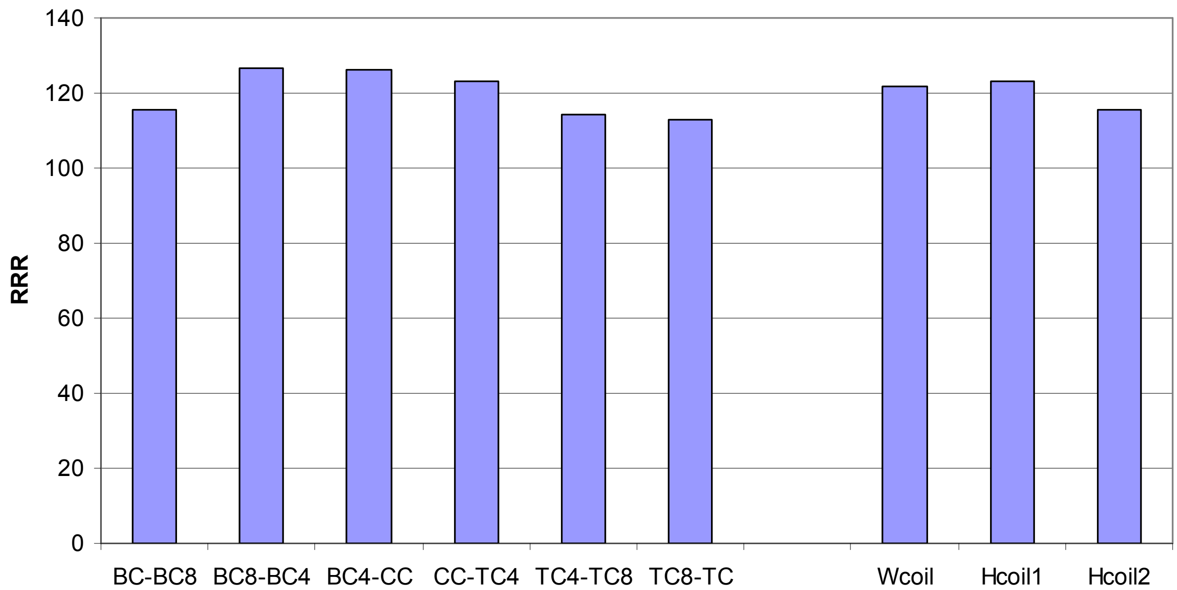

Figure 6. RRR measurements for the configurable voltage tap segments.

Table 3. RRR data for all the CVT segments in SR07; ΔI=19.4 A at 18 K and ΔI=9.2 A at 300 K

Segment	Δ (V+ - V-)	R (cold)		Δ (V+ - V-)	R (warm)	RRR
V1_VoTapBC_BC8M_1	0.0009762660	0.0000503310		0.05353760	0.00582592	115.75
V1_VoTapBC8_BC4M_1	0.0006385470	0.0000329200		0.03833700	0.00417181	126.73
V1_VoTapBC4_CCM_1	0.0005796590	0.0000298841		0.03471410	0.00377756	126.41
V1_VoTapCC_TC4M_1	0.0007256780	0.0000374121		0.04231290	0.00460446	123.07
V1_VoTapTC4_TC8M_1	0.0007291070	0.0000375889		0.03942140	0.00428981	114.12
V1_VoTapTC8_TCM_1	0.0008201040	0.0000422802		0.04388600	0.00477564	112.95
V1_VoTapWcoilM_1	0.0025401400	0.000130956		0.14652700	0.01594540	121.76
V1_VoTapHcoilH1M_1	0.0017335200	8.93712E-05		0.10127000	0.01102040	123.31
V1_VoTapHcoilH2M_1	0.0018057000	9.30921E-05		0.09899870	0.01077320	115.73

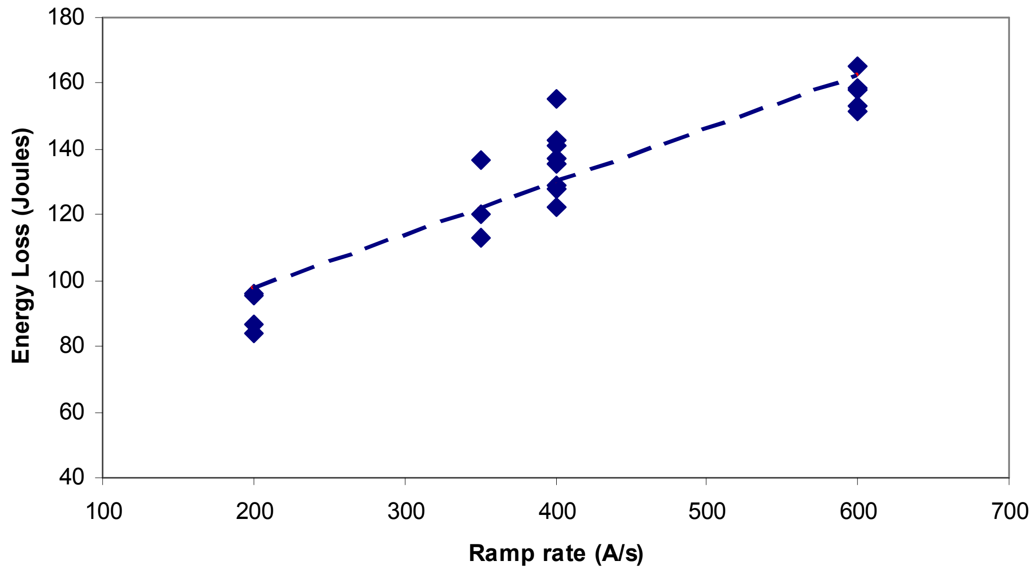

Figure 7. Energy loss measurements at 4.5 K using the *VxWorks* system.

8. Splice Resistance Measurements

We measured the resistance of the NbTi-Nb_3Sn splice at both leads at 4.5 K. The splice voltages were measured as a function of magnet current to determine their resistance. A calibrated Helwet-Packard 3458 Digital Multimeter (DVM) was used to digitize the raw (unamplified) splice voltages. DVM was programmed to integrate over 42 power line cycles in order to reduce 60 Hz noise components. We measured splice resistance at the negative lead first and then at the positive lead of the magnet using the front input of the DVM.

Data and the linear fit are shown in Fig. 8 and Fig. 9. Both splices have expected resistances: 0.24 nΩ in the top layer and 0.27 nΩ in the bottom layer.

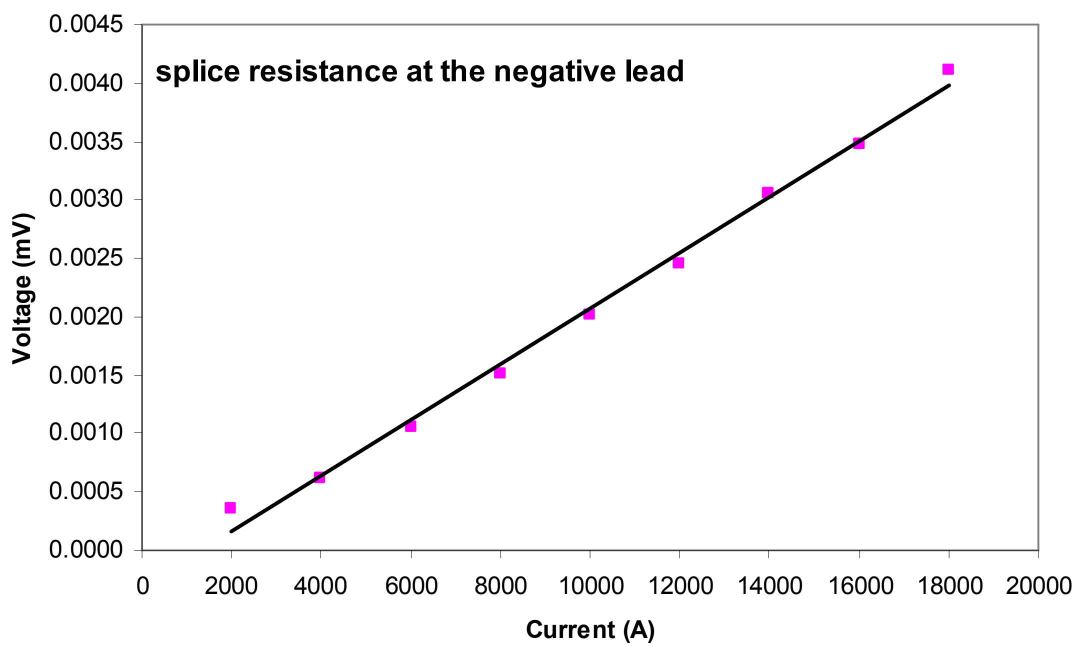

Figure 8. VA-dependence for the top layer splice: data (dots) and linear fit (line).

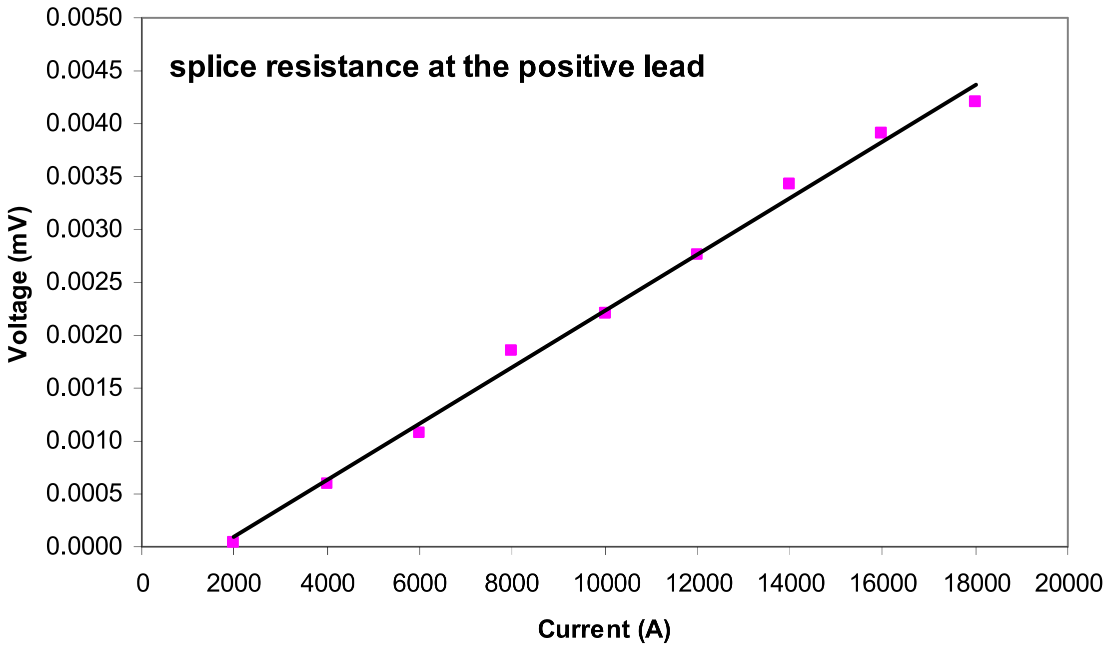

Figure 9. VA-dependence for the bottom layer splice: data (dots) and linear fit (line).

9. Quench Locations

All of the high current quenches at 4.5 K occurred in the top layer except one - the quench #15, which developed in the bottom layer. One should mention that the quench #15 was performed after more than 1 hr. of the heat load study described at the end of Section 3. All remaining quenches in the bottom layer occurred at high ramp rates of 480 A/s and more at 4.5 K. Only the top layer was quenching at 2.2 K and at intermediate temperatures 2.6 K – 3.6 K.

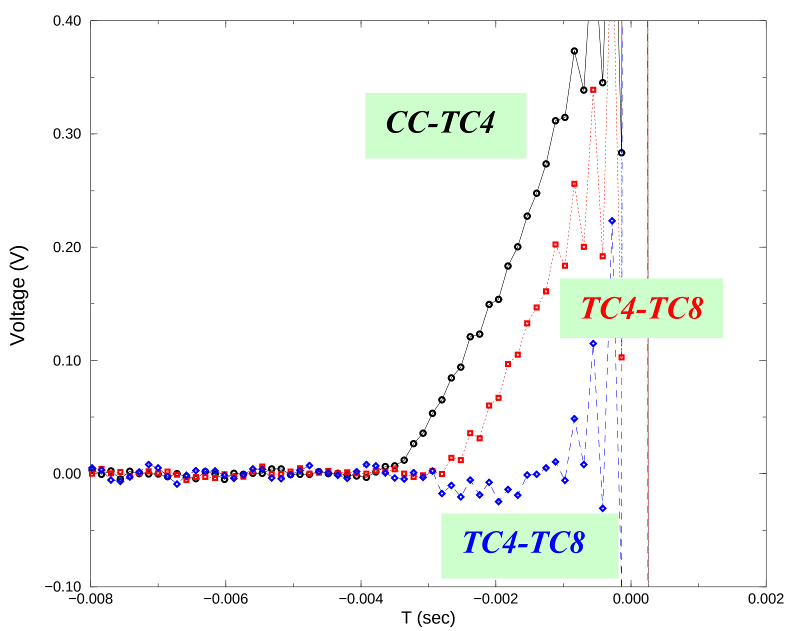

Figure 10. Quench scan data at 100 A/s and 4.5 K operation.

The typical quench pattern is shown in Fig.10. The quench starts in the central multi-turn segment (***CC-TC4*** or ***BC4-CC***) and then propagates to the adjacent segments.

10. Estimated Maximum Quench current of SR07 Magnet

The maximum quench current data of the SR07 magnet are shown in Fig. 11 on its load line. They are compared with the short sample data of the F4 Rutherford cable, which were calculated from the witness samples of round and extracted F4 strands, measured at 4.2 K. As it was mentioned in Section 4, if there were no problems with the SC leads, we could expect the maximum quench current of 24.5 kA at 4.5 K (marked with "•" in Fig. 11) and 27 kA at 2.2 K (marked with "o"), corresponding to 9.7 T and 10.75 T respectively. Based on short sample estimates shown in Fig. 11, the extrapolated maximum quench current of SR07 magnet attained 100 % of the short sample limit.

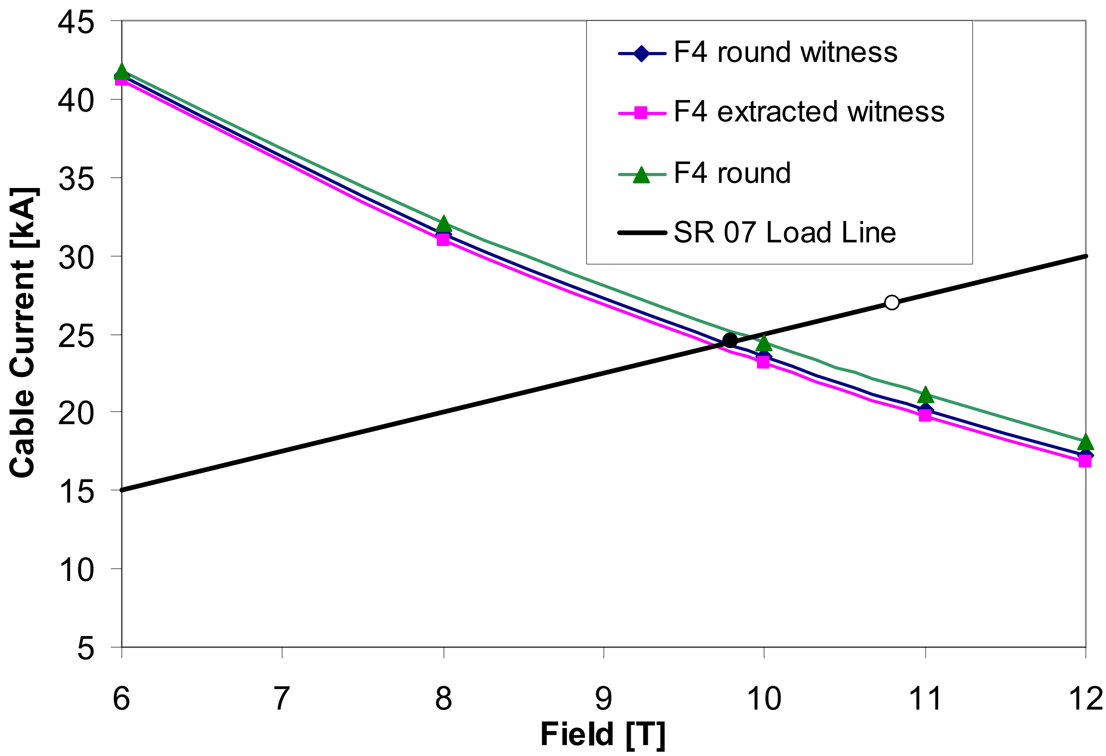

Figure 11. The load line for the SR07 magnet and short sample estimates measured at 4.2 K.

11. Comparison of Data of SR magnets

The test results of all SR magnets are compared in Table 4. The maximum quench currents of SR03 and SR07 magnets in this table are extrapolated data, assuming the power leads are in a good condition. All SR magnets are made of two13 turn-coils, except for SR06, which has two 12 turn-coils.

From this table SR07 test results are remarkable, almost comparable in the maximum current to SR03, although the critical current density (Jc) of Nb_3Al strands is smaller than those of RRP strands. The copper ratio of F4 Nb_3Al strand was intentionally reduced to make its Ic value higher.

Another remarkable feature of the SR07 magnet is that it did not have any training, while other Nb_3Sn magnets had an extensive training. It may be partly explained with improvements in the construction technique, or with the extra hardness of the Nb_3Al strands, which prevents any movement of the coil or cracking of the epoxy.

Both SR03 and SR06 magnets are made of the RRP strands, which have higher critical current density. But these magnets are not always consistent in their performance, probably because of some cable damage.

Table 4. Comparison of data for all SR Magnets

Magnet	Strand, No. of strands	No. of turns	Max. Current	Max. B	Stability	Problems
SR01	Nb_3Sn, MJR x 28	13	24.1 kA, 2.2 K			Training
SR02	Nb_3Sn, PIT x 28	13	20.3 kA, 4.6 K			Training
SR03	Nb_3Sn, RRP x 28	13	27.5 kA, 4.5K 30 kA, 2.2 T	10.9 T 11.9 T	Stable	Training
SR04	Nb_3Al, F1 x 27 Nb matrixed	12	21.8 kA, 4.0 K	9.3 T	Very Unstable	Low field instability
SR05	Nb_3Al, F3 x 27	13	Not tested			
SR06	Nb_3Sn, RRP x 27	12 Keystone	28.6 kA, 4.5 K 26.6.kA, 2.2 K	10.3 T 9.7 T	Some erratic operation	Training
SR07	Nb_3Al, F4 x 28 Ta matrixed	13 Rectangular	24.5 kA, 4.5 K 27 kA, 2.2 K	9.7 T 10.7 T	Stable	No Training

12. Conclusion

Small racetrack magnet SR07 made of the Nb_3Al (F4) cable exhibited stable performance at both 4.5 K and 2.2 K operations.

Several quenches occurred in the SC leads during the cold tests. Thermal load tests confirmed that the copper flag plate soldered with NbTi cable joint might be responsible for the heat generated in the leads. Detailed investigation of the top plate copper block and the copper plate to NbTi cable connections will be performed after the test.

The highest quench current achieved was 22450 A at 4.5 K and 25190 A at 2.2 K. If there were no SC lead trips at low ramp rates one could estimate the maximum quench current from the ramp rate dependence as 27 kA at 2.2 K and 24.5 kA at 4.5 K. Therefore, almost without any training, SR07 magnet reached the short sample limit.

SR07 magnet is the first stable high field dipole magnet built using the fully copper stabilized Ta-matrixed Nb_3Al strand.

References

[1] A. Kikuchi, R. Yamada, et al., "Characteristics of Cu Stabilized Nb_3Al Strands with Low Cu Ratio", to be presented at ASC08 (Chicago), 2008.

[2] M. Tartaglia, R. Yamada, A. Kikuchi, et al., "SR04 Test Summary Report", TD-06-066, 12/4/06.

[3] R. Yamada, A. Kikuchi, G. Chlachidze, et al., "Quench Tests of Nb_3Al Small Racetrack Magnets", *IEEE Trans. Appl. Supercond*., vol. 18 , pp. 1039-42, 2008.

[4] R. Yamada, A. Kikuchi, M. Tartaglia, et al., "Quench Tests and FEM Analysis of Nb_3Al Rutherford Cables and Small Racetrack Magnets", To be presented at ASC08, 2008.

Appendix I: Parameters of F4 Nb_3Al Strand

AI.A Strand Information

PRECONDITION	Small Cu ratio of 0.63, Not gauged , annealed at 400 ^oC for 2 h.
MANUFACTURER	NIMS - Hitachi Cable (precursor) - Hikifune(electroplating)
BILLET #:	ME488 (Hitachi Cable's billet ID)
SPOOL #:	F4
COMPOSITION	276 Nb_3Al subelements, Ta interfilament matrix, Ta central dummy core, Nb skin matrix. Shown in Fig, A1
STRAND DIAMETER	NOMINAL : 0.99mm
Cu/SC RATIO	NOMINAL : 0.63:1
FILAMENT TWIST LENGTH	45 mm DIRECTION : Right hand
SUBELEMENT #:	276
SHARP BEND & ROLLING TEST	Done, shown in Fig. A2 and A3.
CUT LENGTH	472m–(25m x 18 = 450m used) = 22m, 243m-(25m x 9 = 225m used)=18m

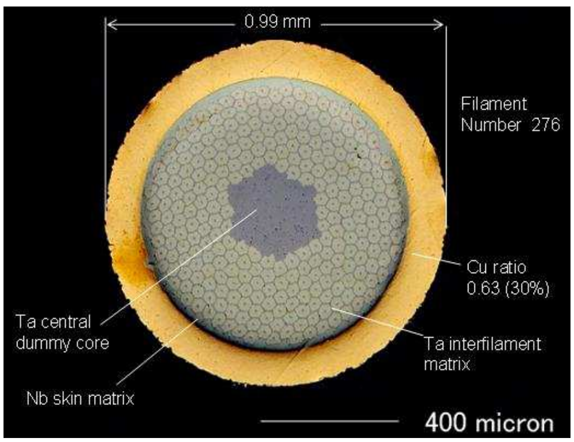

Fig A1. Cross section of F4 strand.

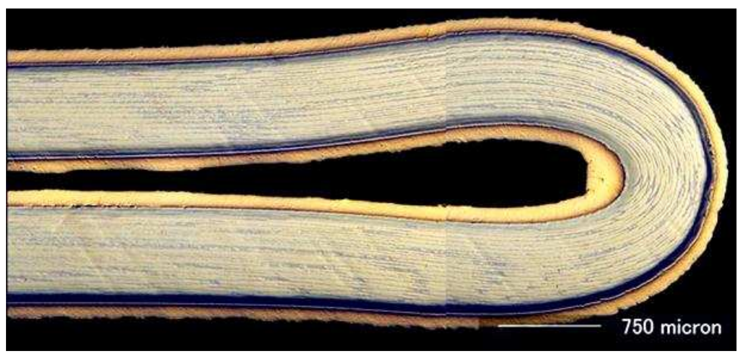

Fig. A2. Bending test of F4 strand

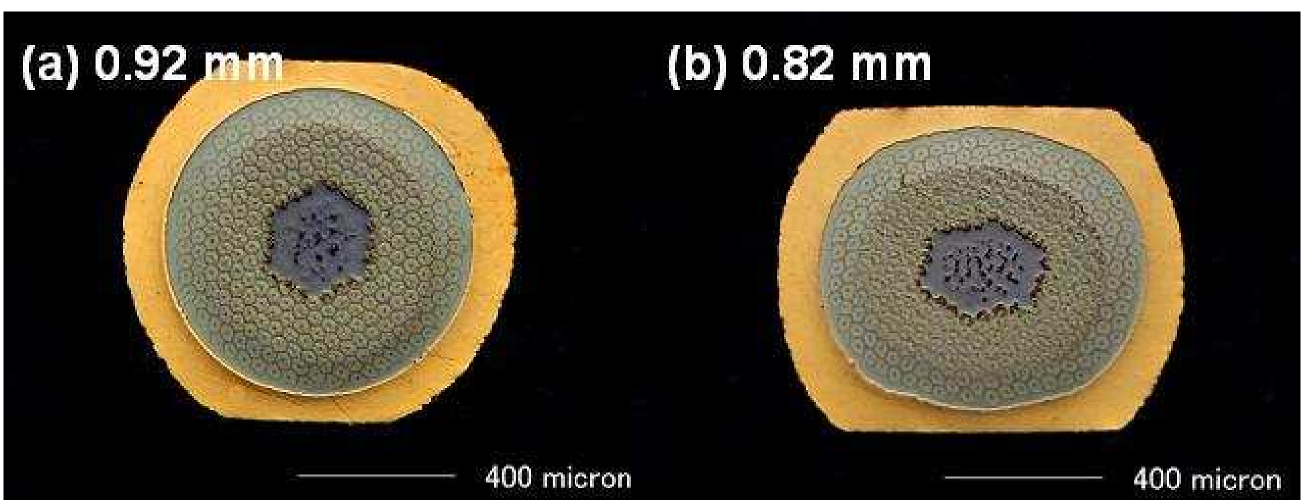

Fig. A3. Rolling test of F4 strand.

AI.B Ic: Short Sample Data of F4 Round, F4 Round Witness, F4 Extracted witness, compared with F3 Round and F1 Round Strands

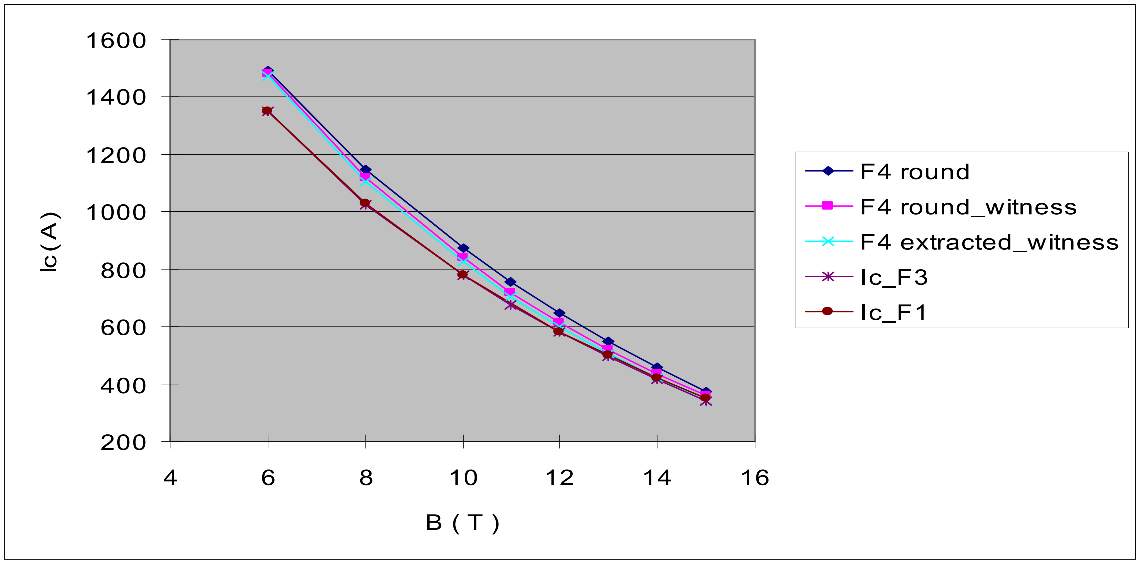

Fig. A4 Short sample data of F4 Strands

Table A1 Short sample data of F4 Strands

Ic (A)						
	F4 round	F4 round wit	F4 extracted	Ic_F3		Ic_F1
15	376.46	358.32	342.74	342.97	15	351.5
14	457.79	437.87	420.5	415.75	14	422.1
13	547.3	519.64	504.18	495.8	13	499.7
12	645.87	615.89	601.35	581.34	12	582.9
11	755.82	720.49	704.96	675.58		
10	872.45	841.59	826.82	779.46	10	779.3
8	1145.19	1118.69	1104.19	1027.07	8	1028.3
6	1491.65	1480.58	1472.32	1352.48	6	1352.1

AI.C Jc : F4 Short Sample Data Round, Round-wit, Ext-wit

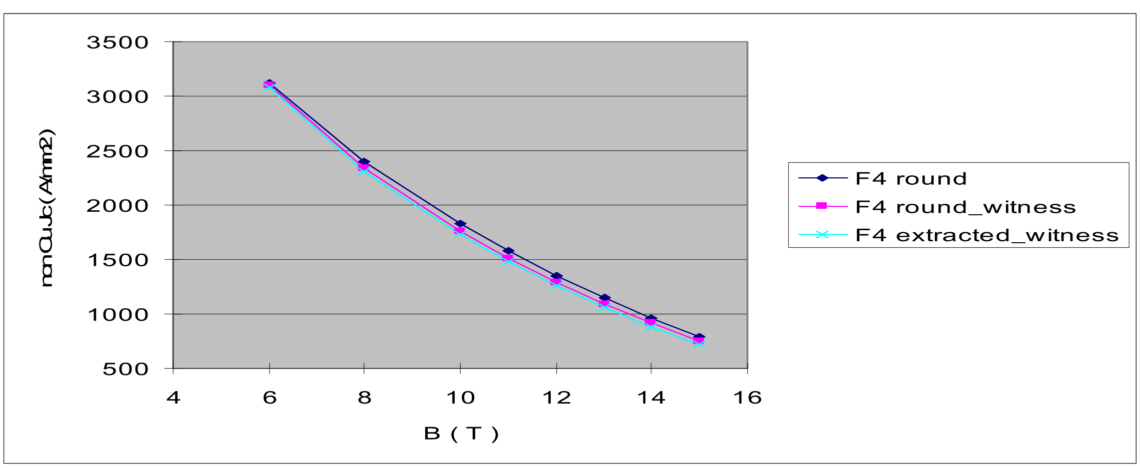

Fig. A5. Jc values of F4 strands.

Table A2. Degradation of Extracted Strand

Ic degradation at the cabling	
	Degradation (%)
15	4.35%
14	3.97%
13	2.98%
12	2.36%
11	2.16%
10	1.76%
8	1.30%
6	0.56%

Table A3 Non Cu Jc of F4 Strands

non Cu Jc (A/mm2)			
	F4 round	F4 round_witness	F4 extracted_witness
15	788.3	750.3	717.7
14	958.6	916.9	880.5
13	1146	1088.1	1055.7
12	1352.4	1289.6	1259.2
11	1582.6	1508.6	1478.1
10	1826.8	1762.2	1731.3
8	2397.9	2342.4	2312.1
6	3123.4	3100.2	3082.9

Appendix II: Parameters of F4 Nb_3Al Rutherford Cable

AII.A CABLING SPECIFICATIONS

Spec. of Strand: Small Cu ratio of 0.63, not gauged, annealed at 400^{o}C for 2 h.
No. of STRANDS: 28 x 0.99 mm, (0.984-0.996 mm)
PITCH DIRECTION: Left PITCH LENGTH: 100 mm
LAY ANGLE: Degrees 15
CABLING SPEED 1/3 m/min. Wheel Rotation Speed 3 turns/min.
Caterpillar tension Rectangular %170 (lb)

LUBRICATION: 1-2 drops of Light oil every 5m
STRAND TENSION: 3.5 ~ 4.25 lbs
Nom. THICKNESS: 1.9 mm Rectangular Cable
Nom. WIDTH: 14.1-14.2 mm
Nom. ANGLE: 14.5 degree

AII.B FINISHED CABLE

RECTANGULAR

FINISHED LENGTH: **18.22 m (good length)** **14 m Used for SR07**
Avg. THICKNESS: **1.85 mm**
Avg. WIDTH: 13.95 mm
PACKING FACTOR 86.5 %
KEYSTONE ANGLE: 0

PRODUCTION HOURS **RESPOOLING 2.0hrs** **CABLING 4hrs**

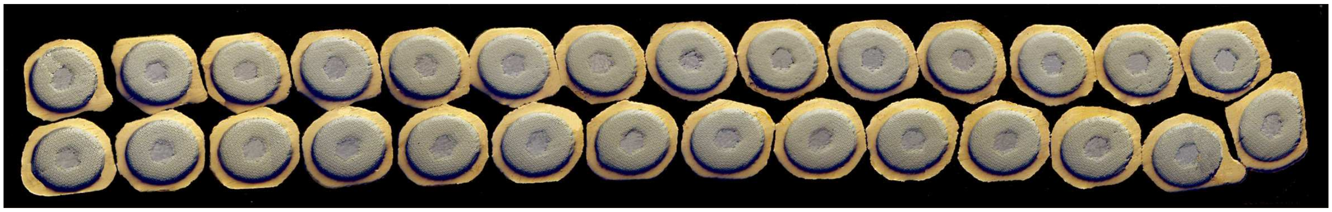

Fig. A6 Cross section of F4 Rutherford Nb_3Al cable.

Fig. A7. Top view of F4 Rutherford Nb_3Al cable. Fig. A8. Side view of F4 Rutherford Nb_3Al cable.

Fig. A9. Witness Sample of F4 Rutherford Nb_3Al cable after heat treated.